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Remote Sensing Technologies for
Monitoring Climate Change Impacts on
Glacier- and Permafrost-Related Hazards

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Remote sensing technologies for monitoring climate change impacts on glacier- and permafrost-related hazards

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Abstract

Glacier- and permafrost-related hazards represent a continuous threat to human lives and infrastructure in high mountain regions. Because the surface and subsurface ice involved is generally close to melting conditions, glacier and permafrost hazards are particularly sensitive to climate changes. The present shift of cryospheric hazard zones due to atmospheric warming, process interactions and chain reactions, and the potential far reach of glacier disasters make it necessary to apply modern remote sensing techniques for the assessment of glacier and permafrost hazards in high mountains. In this contribution we provide an overview of different hazard types and how air- and space-borne remote sensing methods can be applied for their assessment.

Introduction

Disasters associated to the glacial and periglacial environment can cause thousands of casualties in one event. Related damages or mitigation costs are on the order of several 100 mill. EURO as a long-term annual average global sum. Glacier and permafrost hazards in high mountains include glacier- and permafrost-related floods, stable and unstable glacier length changes as well as glacier fluctuations, glacier- and permafrost-related mass movements, permafrost thaw settlement and frost heave, and hazards from glacier-clad volcanoes. Often, combinations of these (and other) processes lead to the most severe glacier catastrophes. Whilst above direct glacier and permafrost hazards are very palpable, so too are indirect hazards, such as changes in dry-season river flows, adverse effects on mountain tourism, and related socio-economic consequences.

Assessment and management of glacial and permafrost hazards require the application of modern integrative earth-observation techniques for a number of reasons:

- Typically, related hazard source areas are situated in remote high-mountain regions, often difficult to access physically for topographic, political and/or security reasons.
- The remote location of most glacial hazard sources, the potential process interactions and chain reactions, and the far reach of some of the high-mountain hazards require remote sensing sensors capable to cover large areas at once.

- Climate change induces disturbance in glacier and permafrost equilibrium and can shift hazard zones beyond historical knowledge. In addition, human settlements and activities increasingly extend towards endangered zones in many regions. As a result, historical data alone are not sufficient any more for hazard assessments and have to be combined with new observation and modelling approaches.
- Due to the current rapid change of high-mountain environments, hazard assessments shall be undertaken routinely and regularly, combined with continuous monitoring. Remote sensing is particularly suited for both regular and rapid observation.

Recent developments in remote sensing open up new possibilities for the assessment of natural hazards in general, and glacier and permafrost hazards in particular (Huggel 2004; Kääb et al. 2005b; Quincey et al. 2005). Remote sensing will therefore substantially gain importance for such works in the near future.

Glacier-related floods

Generally, glacier floods represent the glacial risk with the highest potential for disaster and damages. Glacier floods occur in most glacierized mountains of the world and are triggered by the outburst of water reservoirs in, on, underneath and at the margins of glaciers. Most reservoir types develop slowly and can be identified at the surface, a precondition that favours the application of remote sensing techniques for monitoring glacial and periglacial lakes. Floods from ice-dammed lakes and proglacial moraine-dammed lakes, in particular, represent a recurring and severe danger (Figure 1). Different outburst mechanisms are involved in glacier floods:

Breaching of moraine dams. Trigger for such process are usually enhanced runoff into the glacial lake, impact waves (e.g. from ice, rock or snow avalanches), temporary damming/jamming at the lake outlet, or progressive flow and erosion in the moraine (piping). Moraine-dammed lakes are usually detectable by remote sensing, in particular optical techniques (Figure 1). Time series of images are particularly useful for assessing lake dynamics and estimating future development. The assessment of moraine dam characteristics requires high-resolution and -precision techniques (dam geometry, deformation, settlement, surface material, etc.). Monitoring of associated glacier characteristics (geometry, surface type), changes and kinematics (thickness changes, velocity) may help assessing the evolution of proglacial lakes (e.g. Ageta et al. 2000; Haeberli et al. 2001; Huggel et al. 2002).

Failure or overtopping of ice-dams. For permanent ice dams, the disasters often repeat because the ice dam may recover after an outburst. Related outbursts stem from ice-marginal lakes and from temporary ice dams from ice avalanches or glacier surges. The detection of ice-dammed lakes is depending on the temporal resolution and timing of the remote sensing system applied, the detection of ice dams is depending on the spatial resolution and spectral characteristics. Time series are particularly useful. The monitoring of thickness changes and kinematics of long-lasting ice dams may support the assessment, e.g. of the floatation level (e.g. Espizua and Bengochea 1990; Haeberli et al. 2001; Huggel et al. 2002; Kääb et al. 2003).

Glacier outbursts are catastrophic water discharges from the en- or subglacial drainage system. Glacier outbursts are particularly difficult or impossible to assess

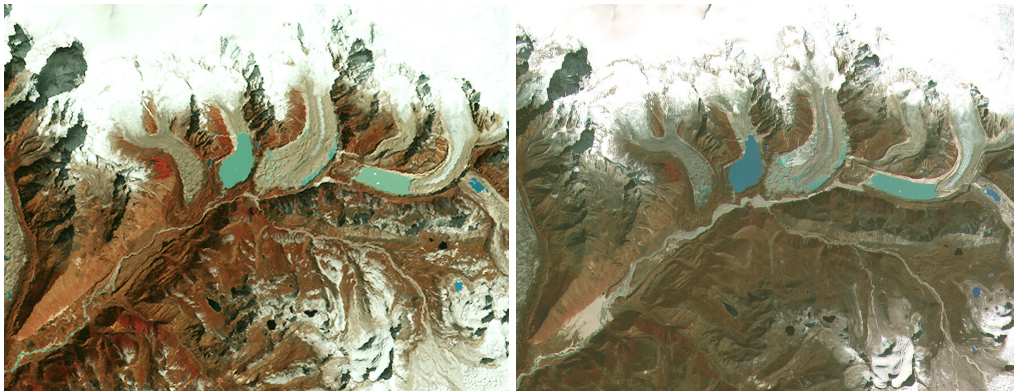


Figure 1: Luana, Bhutan Himalayas (17 x 13 km). Details of a Landsat image of 1990, left, and an ASTER image of 2001, right. Most of the lakes have increased in area between 1990 and 2001, either due to retreat of the calving front, or from growing and connecting supra- and pro-glacial ponds. On October 7, 1994, the lake to the right of the images, Lugge Tsho, burst out and caused a glacier flood.

due to their sub-surface character. An exception from this problem is in some cases the detection of strong sub-glacial volcanic activity.

Breaching of thermokarst and supra-glacial lakes. Thermokarst and supra-glacial lakes can develop on ice-rich permafrost or stagnant glacier ice. Thermal convection leads often to progressive lake growth. Outburst causes are similar to breaching of moraine and ice dams, and, in addition, progressive melt of the ice or permafrost dam. Detection of related lakes usually requires high image resolution due to the small lake size. Time series can be particularly useful (Figure 1). The disposition of lake development is partially detectable through remote sensing of surface characteristics and kinematics (Reynolds 2000; Wessels et al. 2002).

Displacement waves. Displacement-waves impact on people, natural and artificial lake dams, and other installations. Those displacement waves have been the trigger for a number of lake outburst events. They originate from the impact of snow-, ice-, rock-avalanches, landslides, debris flows, etc. into the lake, or from floatation of icebergs. Their assessment requires integrated remote sensing and modelling approaches of source processes.

Glacier length and volume changes

Advancing and retreating glaciers can pose a direct risk to mountain infrastructures. From a global point of view, the prediction of glacier length variations is complicated by the fact that glaciers can vary in a continuous (stable) or unstable way (i.e., glacier surges).

Glacier surges are a temporary instability of large glacier parts with ice velocity increased by an order of magnitude (or more). Usually, glacier surges are accompanied by drastic glacier advance. Surging glaciers are able to rapidly destroy installations or induce other hazards, such as ice- and rock-falls. They can temporarily dam lakes, which, when these dams fail, produce some of the largest known outburst floods. Often, glacier surges are accompanied by enhanced englacial



Figure 2: *Looped moraines on a glacier in the Pamir hint to repeated surge-type activity of the tributary glacier to the lower left. The related surge waves deformed the moraines of the main glacier. (ASTER, 13 x 13 km).*

water storage, which is possibly released at the surge end in a catastrophic way. Surges can be tracked by high-frequency remote sensing (e.g. Espizua and Bengochea 1990). Former glacier surges, and thus surge-type glaciers, can often be recognised from deformed moraines (Figure 2). Geometry changes, if involved in the surge disposition and build-up, may be detected as glacier thickness changes.

Stable glacier advance and retreat. Advancing glaciers may inundate land, override installations, dam rivers and form lakes, cause ice break-offs, etc.. Glacier retreat forms usually no direct hazard but is able to trigger a number of secondary hazards such as various slope instabilities and ice avalanches. Causes for such stable glacier length changes are changes in mass balance and/or in ice dynamics. Stable glacier length changes can usually be monitored by remote sensing: glacier area changes from repeat imagery (Paul et al. 2002; Silverio and Jaquet 2005) and glacier mass changes from repeat digital terrain models (DTM). Forecast of such length changes is best done by a combination of remote sensing, glaciological field work and modelling.

Changes in glacier runoff and seasonality. Glacier mass loss leads to reduction of water resources as stored in glaciers and to changes in dry-season river flows. The short-term perspective is increasing discharge due to enhanced melt; the long-term perspective is decreasing discharge when the glaciers in a basin become substantially smaller or disappear. These processes have consequences for drinking water supply, irrigation, hydropower production, industrial water use, fishery, water quality, etc.. Changes in glacier runoff are best investigated through a combination of remote sensing, meteorology, and combined glaciological and hydrological modelling (Huggel et al. 2003).

Glacial and paraglacial mass movements

Compared to the distances covered by glacier floods, ice and rock avalanches often affect much smaller areas. Corresponding disasters are generally restricted to densely populated high-mountain regions. However, in combination with other hazards, ice and rock avalanches have the potential for far-reaching disasters. In zones with high seismic activity and geothermal heat flow, the risk of major ice break-offs is greatly increased, as was demonstrated dramatically by one of the most destructive glacier catastrophes, the Huascarán disaster in 1970, with a loss of over 18,000 lives. Also, the extraordinary 20 September 2002 rock/ice avalanche at Kolka/Karmadon (Caucasus), a combination of rock and ice destabilisation killing over 100 people, drastically underlines the devastating potential of ice/rock avalanches (Figure 3) (Kääb et al. 2003). A widespread risk in high mountains is related to accumulations of loose sediments on steep slopes, which represent potential sources of debris flows. Such debris accumulations can occur in the form of moraines, moraine dams, or steep valley flanks uncovered by retreating glaciers.

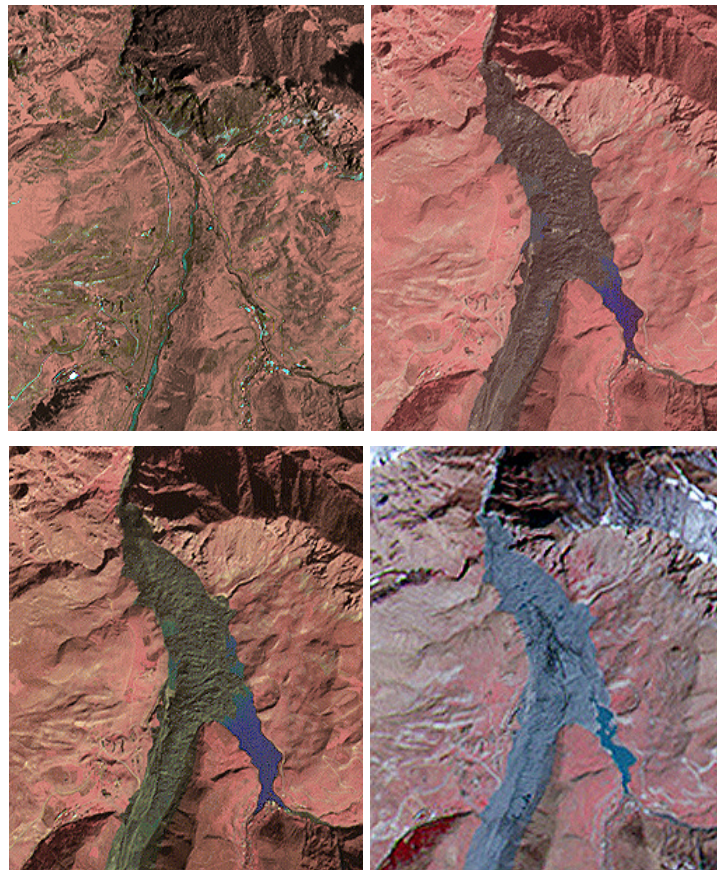


Figure 3: Deposits of the September 20, 2002, rock-ice avalanche at Kolka/Karmadon, North Ossetia, Caucasus. Avalanche direction was from the image bottom to the top. Upper left: June 22, 2001, i.e. before the event. Upper right: September 27, 2002, i.e. shortly after the event. The deposits of about 100 mill. m³ dammed the rivers flowing through the Karmadon area to the north. Lower left: October 13, 2002. Note the changes in the temporary lakes. Lower right: April 09, 2004. The lakes reduced significantly in area or disappeared. The ice dam shows distinct collapse and melt structures. (ASTER, 3.8 x 4.5 km).

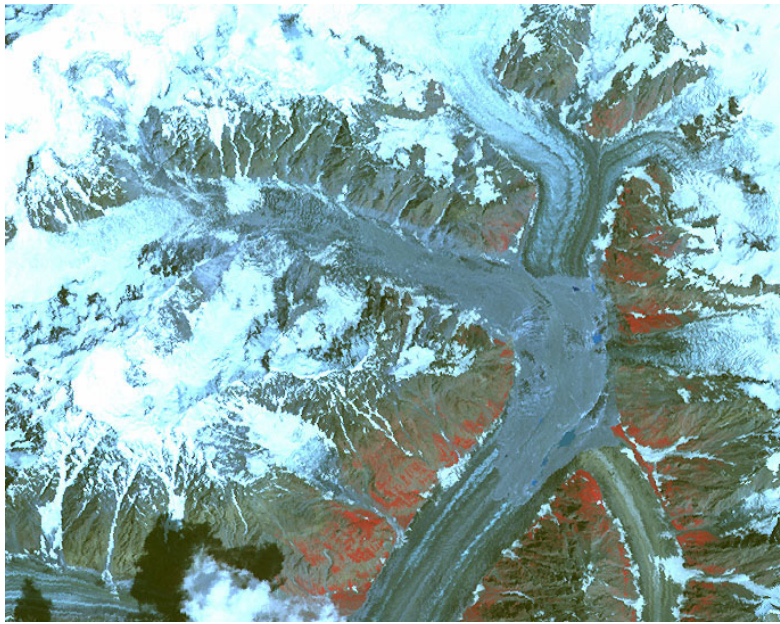


Figure 4: Rock/ice-avalanche event in the Tajik Pamirs from around spring 2002 (ASTER, 2003; 15 x 9 km). The source zone of the avalanche is approximately to the upper left. The avalanche deposits cover an area of roughly $6 \cdot 10^6 \text{ m}^2$, runout distance is roughly 10 km, and vertical drop roughly 2000 m (overall slope roughly 11°).

Ice fall and ice avalanches. Steep glaciers (or glacier parts) are the usual source of ice break-offs and subsequent ice avalanches. In rare cases the detachment of complete glaciers seems possible. Ice avalanches are particularly dangerous in winter with reduced basal friction, extended run-out, and mass gain from snow. Glacier parts can also fail due to a failure of the underlying rock (e.g. Huascaran 1970). Ice avalanches can be triggered by earthquakes. Ice avalanches itself can trigger lake outbursts, dam rivers, or transform into mud/debris flows. Detection of steep glaciers is possible through combination of spectral data with a DTM (Salzmann et al. 2004). High-resolution, -precision, and -frequency remote sensing (e.g. terrestrial close range techniques) enables sometimes the monitoring of mass changes and kinematics related to entire steep glaciers or unstable sections.

Rock fall and rock avalanches. Glacier retreat uncovers and debuttresses rock flanks. The related change in thermal, hydrologic, hydraulic and mechanic conditions can lead to rock fall and rock avalanches (fast mass movement). Rock avalanches can carry parts of overlaying glaciers. Rock avalanches can be of increased magnitude in glacial environments (extended runout on glaciers, or when combined with ice; mass gain from ice; entrainment and liquifaction of glacier parts through impact and transport; detachment of glaciers overlaying the rock mass breaking off) (Figure 5). Rock avalanches can be triggered by earthquakes. Mapping of rock faces and some boundary conditions (e.g. glacier retreat) are possible through remote sensing (Fischer 2004).

Landslides and rock slides. Among other causes, glacier retreat or slope undercutting by floods uncovers and debuttresses rock and debris flanks. The related change in hydrologic, hydraulic and mechanic conditions can lead to mass

movements (slow mass movement). These can create secondary hazards such as river dams. Landslide surface characteristics, geometry and kinematics can be monitored by repeat high-resolution and -precision remote sensing (Kääb 2005; Singhroy and Molch 2004).

Destabilisation of unconsolidated glacial deposits. Glacier retreat leaves unprotected and unconsolidated moraine material that is prone to enhanced erosion and debris flows. Related zones can be detected through remote sensing combined with DTMs (Huggel et al. 2004).

Debris flows from glacier floods. Glacier and permafrost floods are often accompanied by debris flows when erodible material is available in steep parts of the flood path (Figure 1). (See glacier-related floods).

Interaction between volcanic activity and glaciers. Interactions between volcanic activity and glaciers are potentially among the most devastating disasters with glacier involvement. Enhanced geothermal activity, geometric and mechanic changes, deposition of hot eruptive materials, or albedo change by volcanic ash can lead to drastic melt of ice or ice break-off on ice-clad volcanoes and to volcanic landslides or lahars. Ash layers thicker than some mm or cm insulate the underlying ice. Ice cover on volcanoes and its changes (and partially also volcanic activity) can be monitored by remote sensing (Dean et al. 2004; Julio Miranda and Delgado Granados 2003).

Permafrost-related hazards

Permafrost influences the stability and hydrology of debris and rock slopes. Whilst the trigger mechanisms of these frequently unexpected debris flows and rock avalanches often remain unclear (melting dead ice, permafrost-hydrology interactions, etc.) and are therefore difficult to predict in individual cases, the respective hazard potential seems to be connected to the presence of permafrost and its changes. Changes in the thermal regime of cold rock walls and related effects on rock stability are still poorly understood processes but are of increasing concern in view of recent catastrophes (e.g. Figures 3 and 4).

Adverse effects of permafrost creep. Permafrost creep (often forming rockglaciers) can inundate land and destabilise or destroy constructions situated on or in it. Advance of rockglaciers involves continuous transport of surface debris over the rockglacier front. This may lead to local rockfall, endangering people and mountain infrastructure. Monitoring of permafrost deformation is possible by repeat high-resolution optical remote sensing and DInSAR (Bauer et al. 2003; Kääb 2002; Strozzi et al. 2004).

Thaw settlement and frost heave. Changes in ground ice content from ice-lense accumulation or thermokarst processes may result in changes in permafrost surface geometry. Such changes can affect constructions or trigger the development of thermokarst lakes. Thaw and frost heave processes may also be caused by constructions (e.g. changes in snow cover regime, basement heating). Monitoring of geometry changes is possible from repeat high-precision DTMs.

Debris flows from permafrost. Permafrost thaw changes the mechanic and hydrological conditions in permafrost. As a consequence the disposition of

periglacial debris flows may increase. Temporary runoff concentration and ground saturation is, thereby, often involved as trigger. These processes are only detectable using remote sensing when accompanied by changes in surface geometry.

Destabilisation of frozen debris slopes. In rare cases entire sections of rockglaciers or frozen debris slopes might destabilise. Reasons for such processes are largely unknown (dynamics, ground warming?). Such destabilisation can lead to rock fall, debris flows, inundation of land and destruction of infrastructure. Slow movements related to the destabilisation are detectable using high-resolution remote sensing for detecting movement and crevasse formation (Kaufmann and Ladstädter 2002; Kääb et al. 2005a).

Rockfall and rock avalanches from frozen rock faces. The thermal regime and ground ice in frozen rock faces have complex thermal, mechanical, hydraulic and hydrological effects on rock stability. Related changes can cause mass movements. Such processes are often also related to (changes in) surface ice cover (Fischer 2004; Noetzli et al. 2005).

Hazard interactions and integral assessment

The glacier- and permafrost-related processes listed above represent relevant hazard potentials in high mountains on an individual basis. However, combinations and interactions between these or other hazard types are of similar or even greater importance. In fact, many of the largest known glacier catastrophes are characterised by hazard combinations and/or process chains. The assessment of glacier and permafrost hazards requires, therefore, systematic and integrative approaches. Presently, the most successful strategy is based on the combination of remote sensing, modelling with Geographical Information Systems (GIS) or numerical models, geophysical soundings and other local field surveys. These methods are best structured in a downscaling approach from area-wide first-order assessments for systematically detecting hazard potentials (i.e., the domain of space-borne remote sensing and GIS-techniques) to detailed ground-based or air-borne local investigations in high-risk areas (i.e., the domain of geophysics, surveying, and air-borne and close-range remote sensing).

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